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MATERIALS FOR WINGS AND FUSELAGE OF SUPERSONIC TRANSPORTS

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Introduction

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The speed of commercial transport aircraft has increased about fourfold in the past three decades. Increases in size and range have been of the same order. During the next ten years, even this remarkable pace will quicken.

This progress in airplane performance was dependent on, and at times had to await the attainment of, the requisite advances in the underlying sciences and technologies, in such fields as aerodynamics, engines, structural design, and, in many instances, materials. But at no time was it critically dependent on advancements in airframe structural alloys, which have been, and are, aluminum based almost exclusively. The essential requirements of the aircraft designer for airframe alloys have never seriously strained the state-of-the-art of aluminum metallurgy. After all, the DC-3 of the early thirties and much of our modern jet transports are made of the same alloy; only the name has been changed, from 24S to 2024S.

Furthermore, according to recent press reports, the future supersonic transports now in advanced development stages by our competitors, will also be made chiefly of an aluminum alloy, marginally improved in heat-resistance to better withstand the aerodynamic heat that comes with 1500 mph speeds. It is clear that our aluminum alloys not only satisfy the requirements of yesterday's 150 mph DC-3 and of tommorow's 1500 mph supersonic transports; they are the best airframe materials for these transports and for the many others that came between them in time. This is the considered judgment of those whose responsibility it is to know.

Structural Material for Mach 2 - 3

But if our next generation of transports are to fly much faster than 1500 mph -- and the U.S. seems fast approaching a decision that they shall -- there are good reasons for expecting the long reign of aluminum as the predominant airframe material to come to an abrupt end. Aerodynamic heating, which increases sharply at high speeds, since it is a second-power function of Mach number, is the sole basis of this expectation. It is generally conceeded that at speeds somewhat above 1500 mph, the temperature of the airframe will be so high that aluminum alloys, as we know them today, will not be satisfactory.

At Mach 3, approximately 2100 mph, for example, skin temperatures will be as shown in Figure 1. These peak temperatures indicated are equilibrium temperatures which the airframe will experience, and must withstand for at least 30,000 hours. Assuming four flights a day in trans-atlantic service, the airplane will, in the course of its life, undergo thermal cycles, between subzero temperatures and those indicated, upward of 10,000 times. This figure makes the scope and severity of the materials problems that come with Mach 3 commercial flight patently and disturbingly clear to the metallurgist.

Figure 2 attempts to put the Mach 2-3 materials problem into broad perspective, in a very generalized and necessarily imperfect fashion. Looking first at the line marked "temperature," we see how the equilibrium temperature--assuming realistic altitude and emissivity--changes with speed. In the vicinity of Mach 2 the aerodynamic heating is already a source of concern; the structure is slightly hotter than boiling water. Such temperatures obviously will give rise to design problems; eg., insulation and air-conditioning requirements become much more demanding. But still, it is believed that most of our conventional structural materials can accommodate to this temperature by relatively minor modification.

In Figure 2 we see also that between Mach 2 and 3, the temperature of the structure rises increasingly steeply. By Mach 3 the equilibrium temperature has reached about 600 F, and the calculated temperature over the entire airframe becomes as was shown in Figure 1.

Figure 2 also shows how the yield strength in tension, as determined by short-time tests, of some possible airframe alloys will change with speed i.e. with temperature. (The relationship between speed on the abscissa and the temperature on the ordinate is represented by the "temperature" curve.)

It must be emphasized here that the choice of yield strength as the comparison paramenter, and the choice of the specific alloys,are of necessity somewhat arbitrary. There are many other parameters of equal importance, and many other alloys of equal merit, that could just as well have been chosen. But it is believed that these selections are satisfactorally representative, and that essentially the same conclusions would be reached were other parameters or other alloys used.

At Mach 2, aluminum alloy 2219, which is one of the better aluminum alloys for use at high temperature, and one which the French and British studied seriously for possible use in their joint venture with a Mach 2 transport, will still have about 90% of its low-temperature strength. But it is clear that at about Mach 2, this alloy is nearing the brink of a precipitous drop-off in strength. And at Mach 3, it will have left only about 20% of its low-temperature strength. Clearly, a Mach 2 transport made of aluminum would have limited potential for growth to higher speeds.

In Figure 2, we also see that at Mach 3 a representative stainless steels and titanium alloy will still have about 80% of their low-temperature yield strength; and a typical superalloy is scarcely affected at all. Thus, this figure explains the prevailing opinion that a Mach 3 transport, or one that must have potential for growth to Mach 3, should not be made of aluminum.

The Mach 3 Sheet-Material Program

Long-range paper studies of the feasibility and the likely problems of SST have been underway for at least a decade. But for reasons of economy, specific and substantial development work had to await the emergence of the approximate characteristics of the probable airplane, e.g. its speed, size, weight, life-time, flight profile and operating environments. Obviously, such information is needed to establish the materials requirements, which in turn are needed to set the goals of research work on materials.

By late 1960, a school-of-thought holding that the first SST should have Mach 3 potential seemed to have gained ascendance, and preliminary conclusions (1, 2) were reached which enabled materials engineers to estimate materials requirements, and to justify the commitment of substantial research effort to meet them. Obviously, this Mach 3 decision, for reasons touched-on above, forced our SST materials work into steels, titanium, and superalloys, rather than aluminum. French and British studies, on the other hand, led to a Mach 2 decision. Consequently, their materials work has been concentrated on aluminum alloys. Also, at about this same time, a decision was reached that the high costs of the needed supporting research would be too great for individual airframe companies to justify. Consequently, the Federal Aviation Agency, the Department of Defense, and the NASA recommended that they jointly begin a "vigorous effort immediately in order to have an operational aircraft in the 1970 time period".[3] This recommendation was accepted, and has been put into practice.

As one of its several contributions to this SST endeavor, the NASA in February 1961 established the Special Committee on Materials Research for Supersonic Transports, (hereinafter called the Committee). Its mission is not so broad as its name implies; it was the original intent to concentrate attention on sheet materials for wings and fuselage for Mach 3 transports, and this it has done. This committee is made up of representatives of those airframe companies, alloy producers, and government agencies most directly concerned with SST. Its purposes are to provide advice on SST materials research; to make available to all interested parties an instrument for promoting and coordinating research; and to effect a faster and wider exchange of research information.

During its very active two years of life the Committee has assisted in the substantial progress towards these goals. For example, at its suggestion, and under its direction, a report has recently been published that provides a current, comprehensive, and detailed summary of research on Mach 3 SST sheet materials.[(4)] This publication is readily available; consequently there is no need, nor is there sufficient space and time here for detailed presentation of the large amount of newly-developed data. But the scope of the research program under the cognizance of the Committee and its tentative conclusions arrived at after two years of work, will be discussed.

Alloy Screening - In late 1960, it became evident that before work could be started to develop the materials data needed to design a Mach 3 SST, or even to select specific alloys to study extensively, it would be first necessary to eliminate many of the less promising alloys from the many that were being seriously advocated by responsible sources. The NASA, therefore, started a "screening" program in its own laboratories,and under contract in other laboratories, to accomplish this. Later, under the guidance and encouragement of the Committee, other government agencies and industrial companies have supported or conducted additional and complementary screening tests, closely coordinated with the NASA screening work. Some of the first tasks of the Committee were the selection of alloys to be screened, the establishment of conditions-of-test, the defining of the significant parameters for comparison, and the interpretation of results as they accumulated. The alloys that were included in the screening program are listed in Table I. These alloys were selected in the course of several meetings, and with the advise of many representatives of alloy producers and airframe manufacturers. There were some restrictions to admittance to the list. For example, in anticipation of the expected timing of an overall SST project, [3] only alloys that were reasonably well developed,and with which there was a reasonable amount of production experience, were considered. The screening tests were: (1) unnotched and notched tensile tests (ASTM edge notch, chiefly) at temperatures from -110 F to 650 F, and higher in some instances (2) these same tests after 1000 hr exposure at 650 F under realistic stress, and (3) the same tests as in (2), but with the specimens exposed to the corrosive environment of dryed sea salt. The screening program is now nearing completion. Results, as of September 1962, together with conclusion reached by the Committee in the light of data available at that time, are presented in ref. (4). These conclusions are:

1. A Mach III supersonic transport is feasible as far as sheet material for wings and fuselage is concerned. However, it is not evident that either titanium alloys, stainless steels, or a super alloy alone will be best; in all likelihood optimum design will call for more than one materials type (i.e. titanium, stainless steel, or superalloy) and more than one alloy of each type.
2. On the basis of available data, the following alloys are considered to be the most promising ones: Steels - AM350; AM355; PH 14-8 Mo; Titanium Alloys - Ti 8Al 1 Mo 1V; Ti 6 Al 4V; Superalloys - René 41; Waspalloy; and INCO 718.
3. None of the above-listed alloys show significant degradation in strength or toughness after exposure to representative SST stress and temperature for 1000 hours.
4. Failures of some titanium alloys and stainless steels, in laboratory stress-corrosion tests, at representative SST temperatures and in the presences of solid-salt, both with and without high humidity, indicate that further studies are needed to determine the gravity of this phenomenon.

Rating of Alloys - Before reviewing the several post-screening studies, which are intended to provide more complete data on those alloys that survived screening, it is appropriate to examine the various parameters that were used to screen. These parameters are introduced at this time because, in addition to their use in screening judgment, there also provided guidance to the more detailed post-screening investigations mentioned later.

The parameters and their definitions, which are specific to the requirements of a Mach 3 transports, are listed in Table II. Some of these definitions are tentative, and are under continuing study by a Committee Panel. It is not unlikely that revisions will be made in the future. For example, the definition of the "formability" requirement is recognized as being unsatisfactory. It is used only because values of tensile elongation are available. When data from other tests more meaningful to shop formability are available, this definition will likely be changed. It will be noticed also that data needed to evaluate some other of the parameters—"fatigue" on "as-welded strength", for example—will not be forthcoming from the screening tests. Post-screening studies will provide some of this needed, but still unavailable, data.

These parameters are also being used by the Committee as an integral part of a formal procedure for the objective and quantative rating of alloys for Mach 3 SST. Particulars of this procedure are explained in ref. (4). Its approach should be of interest to anyone who has ever been confronted with the complex and perplexing problem of comparing and selecting materials for an entirely novel application.

Fracture Toughness - The small-scale notch tests of the many alloys in the screening program provided useful information on relative toughness. However, fuller characterization of the fracture toughness of the alloys that survived screening was needed. Consequently, and FAA-sponsored contract has been made with the Douglas Aircraft Company to conduct fracture toughness tests with larger specimens (8" and 24" wide).

In this investigation, several variables of importance are being studied, including temperature, crack length, rate of crack growth, and gage. The fracture parameters K_c and K_{1c} will be determined. The alloys used will be: Ti 8Al - 1Mo - 1V; Ti 6Al - 4V; René 41; AM 350 SCT stainless steel; and PH 15-7 Mo stainless steel.

This investigation has been underway for about a year, and substantial progress has been made. At present, however, no data or conclusions are available for publication here.

Fatigue - The effects of the operating conditions of Mach 3 commercial flight on the fatigue properties of the candidate alloys can not be judged satisfactorily on the basis of very limited amount of available fatigue data. The NASA, in its own laboratories are through several contracts, has started research to begin rectification of this situation.

In these studies Ti 6Al - 4V; Ti 4Al - 3Mo - 1V; Ti 8Al - 1Mo - 1V; PH 15-7 Mo; AM 350 CRT, and René 41 are being evaluated. Tests include tension fatigue at 650 F, 70 F, and -110 F; evaluation in fatigue of representative welded and mechanical joints; tension fatigue tests at 70 F after exposure to 550 F for various lengths of time up to three years; determination of crack extension rates; and measurement of remaining strength of fatigue cracked specimens. These investigations, in different laboratories, are using commonly procured material, from the same mill lots. At this writing, these fatigue investigations have been underway for less than a year, and no published results can be referenced.

Creep - At first look, it would appear that significant creep strain will not occur in the fuselage or wings of a steel or titanium Mach 3 transport. These are good for reasons for misgivings, however, in the unqualified acceptance of such a conclusion. For example, there are scarcely any creep data at the stresses and temperature of interest, and extrapolations by the various temperature-time parameters, of higher-temperature shorter-time creep data, are less than completely reliable. It must also be born in mind that in such a large structure as air-transport, the permissible plastic strain can be very small; 0.1% max. has been estimated. Consequently, highly-precise creep data not obtainable in ordinary creep machines are needed. These observations, together with the facts that the structure must last at least 30,000 hours, and will be subjected to cyclic stress and vibration that may affect creep, all dictate a cautious approach.

Consequently, two research projects have been started. Under NASA contract the Convair Division of General Dynamics is developing a specialized creep machine specifically designed to measure very low steady-state creep over very long periods of time. And under an Air Force contract, General Dynamics, Fort Worth, is conducting creep tests, in conventional creep machines, of Ti 8Al - 1Mo - 1V; Ti 6Al - 4V; AM350 SCT; PH 15-7 Mo; and René 41 under test conditions as representative as possible of Mach 3 operations. Results from these studies are not yet available for presentation here.

Stress Corrosion - There is anxiety over susceptibility of the candidate alloys to stress-corrosion under expected Mach 3 operating conditions. This anxiety springs from several sources. For examples, (a) all of the candidate alloys are, of necessity, at very high strength levels for their respective classes; (b) preliminary tests mentioned earlier, and reported in ref. (4), are less than reassuring; (c) the airplane will be exposed to corrosive environment during operations from near-ocean airports, and from salts used on runways for ice removal.

In addition to the screening tests, therefore, stress-corrosion is being studied in a comprehensive program under an FAA-sponsored Air-Force Contract with the Douglas Aircraft Company. Candidate alloys are being evaluated in seaside exposure at Kure Beach and at El Segunda; in laboratory salt-spray tests; in alternate-immersion corrosion tests; and in the presences of dryed salt at high temperature. The study also includes phases intended to clarify the mechanisms of stress-corrosion. Again, published data and reference reports are not yet available at this writing.

Protective Coatings - In the early planning stages of the Mach 3 sheet-alloys program, only alloys that were essentially stainless were given serious consideration. This restraint logically followed the beliefs that a rusty airplane would be unacceptable, and that protective coatings for non-stainless alloys would not be practicable. Obviously, a number of otherwise promising alloys, such as maraging steels, were immediately eliminated.

From a longer-range viewpoint, however, it was deemed worthwhile to conduct a broad survey of all available coatings to estimate their ability to provide protection at Mach 3, and their compatibility with representative non-stainless alloys. Such a survey is being conducted by the Southern Research Institute under an NASA contract. This work has not yet reached a stage that allows reliable conclusions; consequently no data can be presented, or reports referenced, at this time.

Future Additional Research

At this writing, proposals received in response to invitations issued by the Air Force for additional FAA-sponsored projects on Mach 3 SST materials are being evaluated. The final particulars of these contracts are in negotiation, but it is expected that they will be about as follows:

Welding - Properties of fusion welds will be determined by both notched and unnotched tensile tests, before and after exposure at 650°F or 1000 hrs. Some weld restraint tests and fatigue tests will also be made of fusion-welded specimens.

Spot welds will be evaluated by shear and tensile tests, both before and after exposure at 650 F for 1000 hours. Final decision on the alloys to be used are not yet available, but it is fully expected that the several leading alloys under study in the more advanced projects mentioned above will be the ones used.

Fatigue - The current fatigue investigations summarized above will be extended to include tests of leading materials after exposure at 650 F for various long periods of time under load; the current specimens, it will be recalled, are not stressed. Fatigue tests will also be made under conditions more realistically representative of actual Mach 3 operating conditions.

For example, load and temperature spectra will be programed to simulate ground-on-ground cycles, gust loads, maneuver loads, thermal stress, etc. Consideration is being given to the addition of corrosive environments typical of expected operating conditions. In these additional fatigue investigations Ti 8Al 1V 1Mo, AM 350 SCT, and René 41 will be used.

Conclusion

Considering airframe sheet-alloys only, it is a great leap forward to go from subsonic speeds to Mach 3; the problems are greater by an order of magnitude than in going to Mach 2. For at Mach 3, as we have seen, aluminum must be abandoned, and with it are lost much of our efficient, reliable, and economic manufacturing technology, tried and proven design data, as well as maintenance and repair experience. In place of aluminum, we must select from among many different alloys of several general classes, many of which are relatively new and strange; some are so new that their treatment, and even their compositions seem not yet firmly established. The materials engineer must, in a very short time, identify and solve the many problems that will arise with such radical departure from past experience. And he must do so without violating the severe and inflexible restrictions that commercial air transports impose in safety, reliability, and economy. On top of this formidable challange must be added the heavy penalties for failure. For the success of what may well be a billion-dollar venture into an intense and unforgiving competition in which there may be no second place, as well as the prestige of our aircraft industry, will ride with critical decisions that must be made in the very near future.

Clearly, such a fateful and great leap forward calls for the proverbial look. The sheet-materials program briefly summarized here can be though of as one attempt to see where such a leap might land us. Thus, the challenge posed by the Mach 3 SST is grave and urgent, and the stakes are high. This work already underway is but a start on a long and difficult road.

In any research effort to reach specific goals, such as the program described here, very helpful assistance is often to be found in other research efforts with common or similar problems. Our technical societies are useful as instruments of communication for the achievment of such mutual assistance. Liaison therefore, has been maintained between this Mach 3 SST sheet-alloy program and the ASTM-ASME Panel on Structural Materials for Airframes and Missiles, and also, the Aerospace Research and Testing Committee of the Aerospace Industries Association. The many recommendations, and formalized test and analysis methods, of the ASTM Special Committee on Fracture Testing of High Strength Metallic Materials were heavily drawn upon, and were very helpful, in the fracture tests of this SST work.

References

1. The Supersonic Transport - A Technical Summary - NASA TN D-423 June 1960.

2. Supersonic Transports - A Report by the Supersonic Transport Group, Bureau of Flight Standards - Federal Aviation Agency March 1961.

3. Commercial Supersonic Transport Aircraft Report - by Task Groups from Department of Defense, National Aeronautics and Space Administration and Federal Aviation Agency June 1961.

4. NASA TN "Progress Report of the NASA Special Committee on Materials Research for Supersonic Transports" (to be published).

TABLE I

ALLOYS OF SST SCREENING TESTS

STEELS	Ti ALLOYS	SUPERALLOYS
	Ti 6AL1Mo1V	INCONEL 718
PH15 - 7Mo RH1050	Ti 6AL4V	RENE 41
PH15 - 7Mo CH900	Ti 5AL2.5Sn	WASPALLOY
PH14 - 8Mo SRH950	Ti 4AL3Mo1V	R27
AM350 CRT	Ti 5AL2.75Cr 1.25Fe	D979
AM350 SCT	Ti 8AL1OV	INCO 901
AM355 CRT	Ti 13V11Cr3AL	L605
AISI 301 CR (34,51,60%)		V36
		A286
		N155

TABLE II

MATERIAL RATING PARAMETERS FOR SUPERSONIC TRANSPORTS

1. Strength -	The average of the short time ultimate tensile strength and compression yield strength at room temperature and 650°F divided by the material density.
2. As-Welded - Strength	Ratio of the ultimate as-welded tensile strength to the ultimate design tensile strength of the parent metal.
3. Fatigue -	Fatigue strength (10^5 cycles of axial tension, R = 0, and a stress concentration factor of $K_t = 2.5$) at room temperature divided by density.
4. Stiffness -	The average Young's Modulus in tension between 70° and 650°F divided by the material density.
5. Thermal - Stress	Average coefficient of thermal expansion between 70° and 650°F times Young's Modulus at 650°F divided by compression yield strength at 650°F.
6. Toughness -	Minimum values of notched over unnotched tensile strength ratio in the temperature range -110° to 650°F. The choice of ASTM machined edge notched specimen or 8" fatigue cracked specimen should be based on the amount of test data available. Only one type of specimen (either notched or cracked) should be used in the rating procedure. If the amount of data for notched and cracked specimen is approximately the same, the cracked specimen is recommended.
7. Stability -	Ratio of the exposed notched over unnotched tensile strengths divided by the unexposed notched over unnotched tensile strengths. There is a choice of machined or cracked specimen as noted in the toughness parameter. It is recommended that the specimens be notched after exposure if notched specimens are used.
8. Cost -	The product of the cost (dollars per pound) of 10,000 pounds of sheet material (050" x 36" x 96") and 10^5 divided by the strength parameter (refer to strength).

9. Availability - Relative supply of raw material and equipment for production by 1965.

10. Producibility - Producers capability to offer raw material in form of sheet, foil, and plate.

11. Formability - Uniform elongation of 3% in 2 inch gage length.

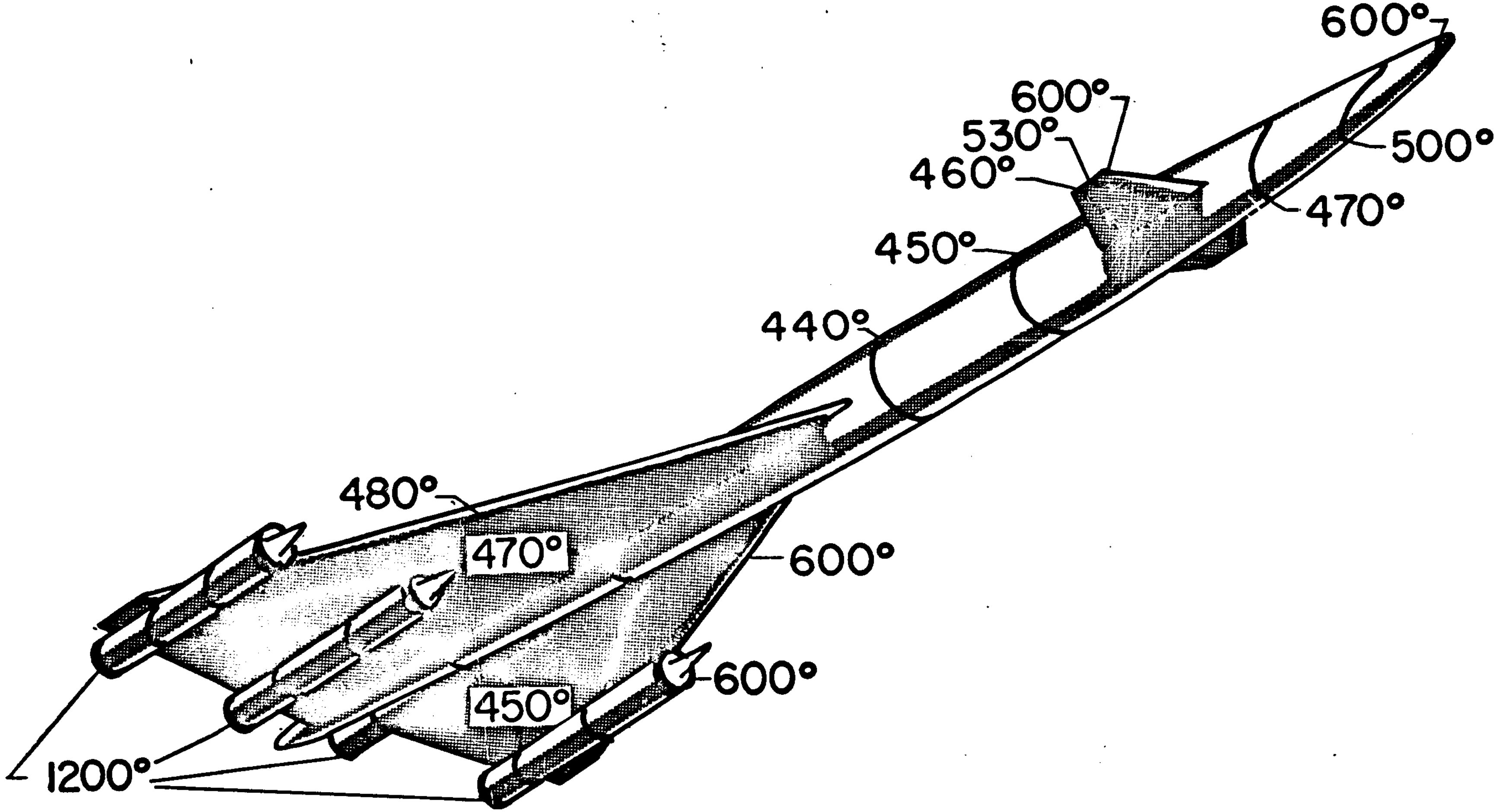
12. Corrosion - Resistance to general corrosion and stress corrosion for supersonic transport environment and life.

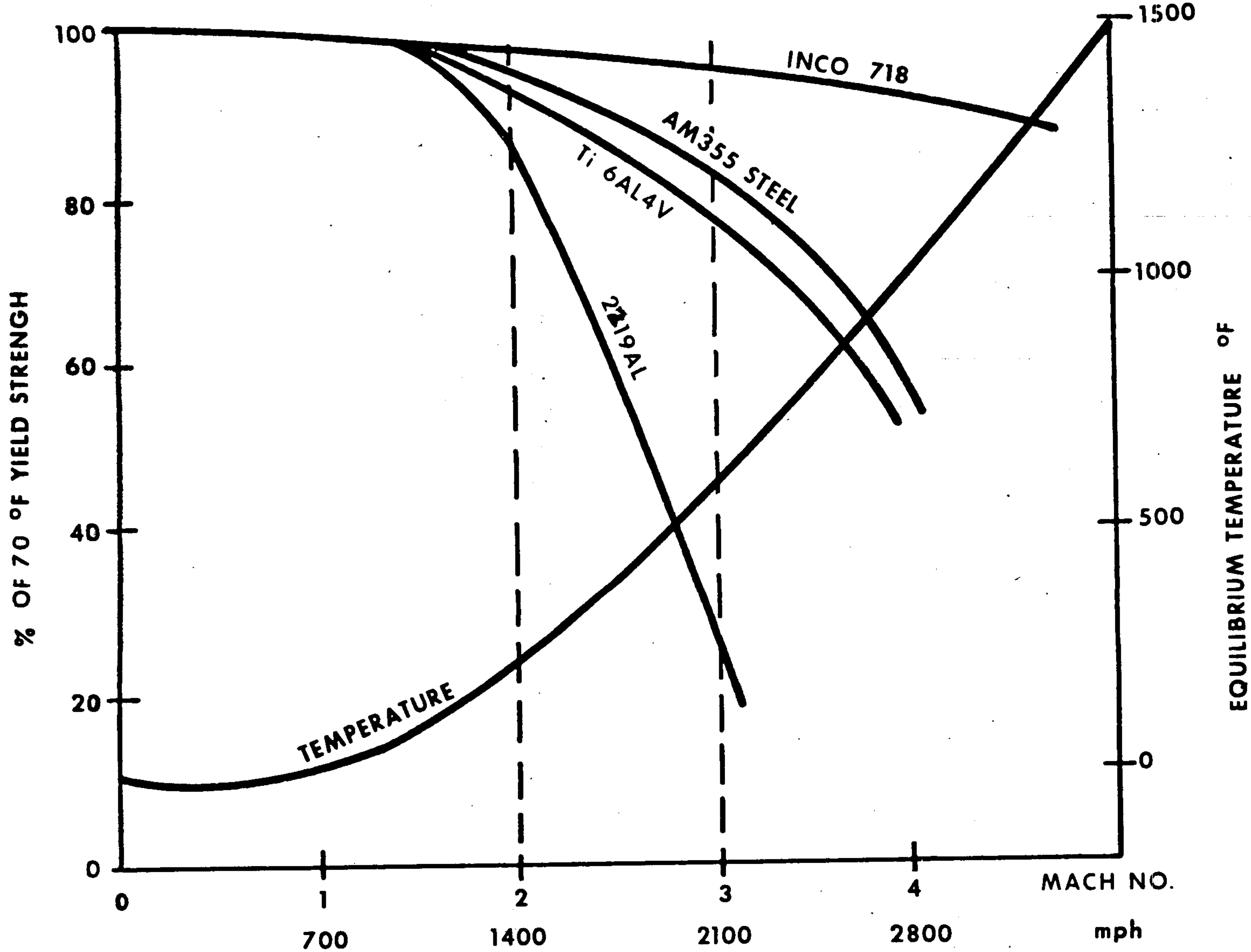
13. Weldability - Can be fusion welded with freedom from voids and cracks.

14. Brazability - Capability, as a brazed sandwich panel, to retain the properties of the brazed material.

M=3 TRANSPORT

PEAK EXTERNAL SKIN TEMPERATURES, °F





EFFECT OF SPEED ON TEMPERATURE OF AIRCRAFT STRUCTURE

NASA RM63-834